Insertion device operating experience at the Advanced Photon Source

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The Advanced Photon Source has 29 insertion devices (IDs) installed in the 7 GeV electron storage ring; 28 of these devices, most of which are 3.3 cm period undulators, use two horizontal permanent magnet structures positioned over a straight vacuum chamber. A support and drive mechanism allows the vertical gap between the magnet structures to be varied, thus changing the x-ray energy produced by the ID [J. Viccaro, Proc. SPIE **1345**, 28 (1990); E. Gluskin, J. Synchrotron Radiat. **5**, 189 (1998)]. Most of these IDs use a drive scheme with two stepper motors, one driving each end through a mechanism synchronizing the upper and lower magnet structures. Our experience in almost 5 yr of operating this system will be discussed. All of the IDs are in continuous operation for approximately 10 weeks at a time. Reliability of operation is of paramount importance, as access to the storage ring for servicing of a single ID inhibits operation for all users. Our experience in achieving highly reliable ID operation is reviewed. Accuracy of operation and repeatability over time are also vital. To this end, these devices use absolute optical linear encoders with submicron resolution for primary position feedback. Absolute rotary encoders are used as a backup to the linear encoders. The benefits and limitations of each type of encoder, and our experience dealing with radiation and electrical noise are reviewed. The insertion devices operate down to gaps as small as 8.5 mm, with clearance over the vacuum chamber as small as 200 μm. The vacuum chamber has a minimum wall thickness of only 1 mm. A number of levels of safeguards are used to prevent contact between the magnet structure and the vacuum chamber. These safeguards and their evolution after gaining operational experience are presented.
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I. INTRODUCTION

The Advanced Photon Source (APS) insertion device designed and built by STI Optronics has proven quite reliable and very accurate in service. We are routinely achieving better than 5 μm gap repeatability. The majority of devices run for several years without causing any interruption of user operations. This is attributable to a solid initial design, refinement of several subsystems over time, routine maintenance, monitoring of device performance, and periodic mechanical adjustment and calibration.[1,2]

The device layout is shown in Fig. 1. Key elements are a large, C-shaped aluminum frame, linear bearings guiding the magnets on the closed side of the C-frame, linear encoders spanning the gap near each end of the device, and two drive screws to position each magnet. The device is mounted to a base fixed to the storage ring floor. The insertion device (ID) vacuum chamber is independently supported from the open side of the C frame by columns secured to the floor. The position of the device relative to the chamber has been very stable. Due to the size of the storage ring, periodic realignment of the vacuum chamber is required due to larger-scale shifts in the storage ring floor. This necessitates realignment of the ID to the chamber, but there has not been an instance of a local floor shift affecting the relationship of the chamber to the ID.

While an allowance for a 5 mm difference in gap from one end of the device to the other addresses the practical need for tapering an ID, the design of the APS ID support and drive mechanism allows the magnets to be fully tapered—they can literally be fully opened at one end and closed to the point of damaging the magnets and ID vacuum chamber at the other. This freedom creates the need for safeguards against excessive taper to protect the chamber and the magnets, but it prevents a mechanical failure (caused by binding of the support and drive mechanism) from damaging the chamber or magnets. From a kinematic viewpoint, the key variables in ID control are simply the magnet gaps at each end of the device. However, due to mechanical, structural, and packaging considerations, the drives are offset well in from the ends of the magnet structures. Therefore, the magnet gap at each end of the device is determined by the position of both drives.[3]

II. EXPERIENCE IN OPERATING THE INSERTION DEVICE

The ID drive scheme uses nonrotating acme screws and bronze nuts driven by the output side of a hollow-shaft wormgear reducer to position the magnets. A triangular linkage is used to resist the reaction torque on the screw from friction with the nut. While screws of this type are very inefficient, this inefficiency means they cannot be backdriven, so they hold their position without requiring a holding torque on the nut. Similarly, the wormgear reducer efficiency is poor, but the reducer cannot be backdriven; the

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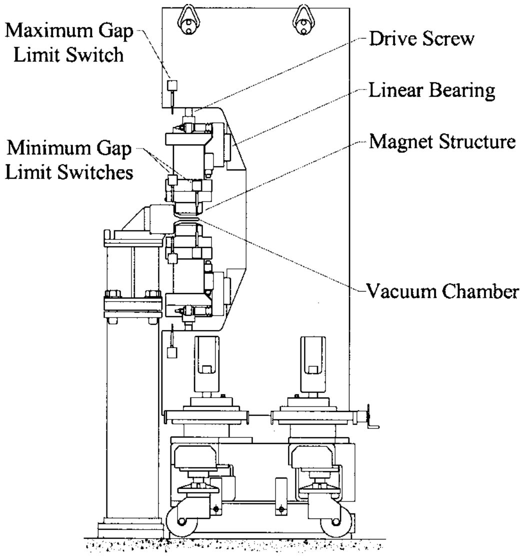

FIG. 1. End view of a typical insertion device installed in the APS storage ring.

output shaft holds its position without a torque applied to the input side. With the screw/reducer combination, the stepper motors can be used without holding current. In practice, a holding current on the stepper motors of 1/3 running current is used. The linkage for resisting screw rotation works fine but requires precise adjustment so that it can freely follow the movement of the screw without loading it axially, which affects gap accuracy.

Four ''drive'' mechanisms are used, one for each end of each magnet. Driveshafts for the upper and lower mechanisms at each end of the device are linked by sprockets and chains to a dual-output bevel gear reducer, driven by a single stepper motor. The drives are synchronized with the chains and the ID is precisely aligned so the gap movement is symmetrical about the vacuum chamber. This arrangement has proven to be very robust, but the chains need to be routinely cleaned, lubricated, or replaced otherwise their efficiency decreases after approximately 12 months of service, due to degradation of the lubricant. Other lubrication requirements have been routine. The oil in the wormgear reducers and the bevel gear reducers is replaced on a preventive maintenance schedule. There have been no failures of these reducers or degradation in their performance. Analysis of the lubricant shows no unique breakdown attributable to radiation.

A flex-disc coupling is used between the motor and the bevel gear reducer. The coupling allows for some angular and parallel misalignment between the motor and reducer. We have had several failures of the flex disks, which are a fiber–resin composite. When the disk fails, the device can still be driven, but the speed must be reduced due to backlash in the coupling causing an impulse torque. We speculated that the disk failures were due to radiation damage, as the disk lies close to the plane of the stored beam. Further testing has led us to attribute the failures to improper installation or handling of the coupling during assembly and installation. Couplings assembled with the proper torque on the screws securing the disks, and then installed without excessive compression, tension, or bending show no signs of wear after 3 yr of operation.

The linear encoders mount to a guide mechanism, which is fixed to the magnet structures at each end of the device with spherical bearings. This assembly is offset from the magnets and is mounted to the side of the magnet structures, spanning the magnet gap. A change in cant of the magnet structures (roll axis of the beam direction) can introduce an error in the encoders due to the offset from the magnet centerline. Careful adjustment of a heavily spring-loaded mechanism that allows cant adjustment is required to prevent a cant change from affecting gap accuracy.

III. MAIN FACTORS IN RELIABLE ID OPERATION

The stepper motors themselves are inherently well suited to a radiation environment, and the ones used are specifically designed with radiation-tolerant materials. There have been no failures of these motors. The stepper-motor drives are not particularly suited to this use due to the electrical noise they produce and the considerable distance from the motors, requiring nearly 40 ft of cable. However, noise suppression has been successfully developed and implemented to prevent interference on ID limit switch and position feedback circuits. The drive system is very robust-the gear reducers have exhibited no failures. We replaced a number of chain sprockets due to bearing wear and replaced all of the chains prior to regular lubrication of them.

IV. ACHIEVING ACCURATE ID OPERATION

We use an absolute linear encoder near each end of the ID to measure the magnet gap. As a backup, an absolute rotary encoder driven by the output of each upper worm gear reducer is also used. For the accuracy, packaging, long-term stability, and serviceability requirements of this application, optical linear encoders are really the only practical position feedback devices available. There are differences in how the ''absolute'' capability of the two encoders is achieved. The linear encoders use two sets of markings on a common scale—an incremental track and an absolute track. The incremental track is read with quadrature decoding from a photodetector and has proven very reliable. The absolute track is read with a 256-element linear charge coupled device and has been prone to degradation and ultimate failure over time due to radiation exposure. Subsequent shielding of the linear encoder read head or the entire encoder assembly with 3-mm-thick lead has so far prevented further encoder failures. The rotary encoder uses a more complex scale with a single photodetector. We have had a small number of failures we believe were caused by radiation damage, but these were either in early operation in a sector with a 5 mm vertical aperture or in a sector where large intentional beam missteering was done.

The encoders are calibrated three or four times a year using measurements of reference gauge pads on the magnet structures. These pads allow measurement of a precise analog to the ID gap even with the device spanning an ID vacuum chamber. This calibration allows typical unidirectional repeatability of the ID gap at each end to within 5 μm or better and typical bidirectional repeatability to within 25 μm or better.

V. SAFEGUARDS FOR ID OPERATION

Software limits establish the normal operational limits for an ID gap. The maximum gap is simply a function of the ID mechanism. The minimum limit is based on consideration of the power handling capability of front-end components, the minimum gap required by the user, the minimum practical gap for the type of ID magnet structure, the mechanical capability of the device, and the vertical size of the ID vacuum chamber. A separate ''beamline limit'' can also be set to a user-specified value to independently raise the operational limit of the ID to protect beamline components from excessive power. Typically, 0.5 mm beyond each software limit are motor step-count limits, independently limiting the distance a motor will move.

Limit switches are used to prevent unwanted ID gap motion and to indicate ID gap status.[4] One maximum gap limit switch and two minimum gap switches are used at each end of each magnet structure. These switches are only hit if an out-of-design condition, such as erroneous encoder feedback, occurs with the control system. The maximum gap limit switches and half the minimum gap switches are used as logic inputs. When such a switch is hit, the device gap can be restored remotely to the normal operating range by APS Operations personnel. The other four minimum gap limit switches are hardwired to a relay chassis and are set to trip at a gap slightly smaller than the logic switches. The relay chassis provides input power to the stepper-motor drives and interrupts this power when a limit switch is hit. Due to the seriousness of such an event, the device gap must then either be manually opened (requiring an access to the storage ring) or the input relay chassis must be manually bypassed to allow motor operation after diagnosis of the cause of the switch trip. Due to the drive configuration (drive screws for either end well inboard of the magnet end), these four limit switches are the final safeguards against contact of the device with the vacuum chamber if a taper condition exists. The type of control system problem that would allow one of these ''relay limits'' to be hit is likely to also cause a taper condition (gap larger at one end than the other).

Mechanical ''hardstops'' are used on the drive screws. They limit the range of motion of each drive screw. This prevents the insertion device from breaking itself and also prevents contact with the vacuum chamber as long as the ID gap is not tapered. A final type of limit switch is used to indicate whether an ID is closed to a gap at which x rays are produced. These beam position limit detection switches are made when the device is opened large enough that the ID is producing essentially no power. The proper operation of all the limit switches on each installed device is verified during each maintenance period.

The maximum gap hardstop design and the ''relay limit'' implementation both evolved from past operating experience. The original maximum gap hardstop design was outboard of the drive screw; it served as a fulcrum during a large taper condition, creating sufficient leverage to stress the screw coupling beyond its design limit. The minimum gap limit switches now hardwired through the relay chassis were originally processed through a logic chip as the other limit switch inputs are. The relay chassis provides an independent chain of safety in the event of a failure of the logic or motor controller card.

VI. CONCLUSIONS

A few design and operational elements have been key to successful operation of the insertion devices. Optical linear and rotary encoders have been reliably used for position feedback in a harsh radiation environment, partly due to lead shielding of several forms to minimize radiation damage. Stepper motors are ideally suited to the radiation conditions and have been completely reliable. The electrical noise problems of the stepper-motor chopper drives have been addressed through filtering and careful cable routing. A simple mechanism incorporating chains and sprockets to link upper and lower magnet drives has proven reliable and readily maintainable.

ACKNOWLEDGMENT

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[4] M. Smith, M. Ramanathan, J. Grimmer, and M. Merritt, Proc. SRI, Stoughton, (2001).